FABRICATION AND TESTING OF A COLLECTOR-CUM-STORAGE TYPE OF SOLAR WATER HEATER

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CERTIFICATE

This is to certify that the work on "Fabrication and Testing of a Collector-Cum-Storage Type of Solar Water Heater" has been carried out under my supervision and has not been submitted elsewhere for a degree.

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NOMENCLATURE

A_c	Exposed surface area of the collector, m^2
b	Tilt angle of the collector with the horizontal, radians
c	Convection coefficient (see page 42), $kcal/m^2\text{-}h\text{-}(°K)^{5/4}$
c_p	Specific heat of water at constant pressure, kcal/kg-°C
d	Declination of the sun, radians
d_c	Thickness of insulation, m
f	Constant in Eqn. (3-21)
h	Hour angle from noon, radians; convective heat transfer coefficient (see page 42), $kcal/m^2\text{-}h\text{-}°C$
H	Total radiation intensity on a horizontal surface, Langleys/min
H_D, H_S	Direct radiation and sky radiation components respectively on a horizontal surface, Langleys/min
H_T	Solar radiation incident normally on the collector surface in Eqn. (3-7), $kcal/m^2\text{-}h$
k_c	Thermal conductivity of insulation, kcal/m-h-°C
l	Latitude of place, radians
m	Total mass contained in the collector, kg
$\dot{m}$	Mass flex density of water flowing past the absorber plate, $kg/m^2\text{-}h$
n	Number of glass plates in Eqn. (3-21)
q_a	Energy absorbed by the blackened plate, $kcal/m^2\text{-}h$
q_b	Energy exchange between the back plate and the surroundings, $kcal/m^2\text{-}h$

q_1	Total energy loss, kcal/m^2-h
q_{roc}, q_{gor}	Energy exchange by convection and radiation respectively, from the glass plate to the surroundings, kcal/m^2-h
q_u	Upward energy loss from the collector surface, kcal/m^2-h
q_w	Energy utilized by water, kcal/m^2-h
R_D , R_S	Orientation factors for direct and sky radiation
t_a	Temperature of ambient air, °C
t_{aav}	Average ambient temperature, °C
t_{a1}, t_{a2}	Ambient air temperatures at the start and the end of an hourly interval, °C
t_b	Temperature of the back plate, °C
t_g, T_g	Temperature of glass plate, °C and °K respectively
t_p, T_p	Temperature of absorber plate, °C and °K respectively
t_{pav}	Average temperature of absorber plate, °C
t_{p1}, t_{p2}	Absorber plate temperatures at the start and the end of an hourly interval, °C
T_s	Equivalent sky temperature, °K
t_{wc1}, t_{wc2}	Average water temperatures at the start and the end of an hourly interval, °C
t_1, t_2	Water temperatures at the inlet and the outlet of the solar water heater
q_{pgc}, q_{pgr}	Energy exchange by convection/conduction and radiation respectively, from the absorber plate to the glass cover, kcal/m^2-h.

U	Overall heat transfer coefficient between the collector and the surroundings, kcal/m^2-h-°C
U_B	Overall heat transfer coefficient between the back plate and the surroundings, kcal/m^2-h-°C
U_L	Overall heat transfer coefficient between the absorber plate and the surroundings, kcal/m^2-h-°C
	Absorptivity of blackened plate
ϵ_g	Emissivity of glass plate
ϵ_p	Emissivity of absorber plate
θ_H, θ_T	Angles of incidence of direct sunlight on a horizontal and an inclined surface respectively
λ	Wave-length, microns
σ	Boltzmann's constant
τ	Transmissivity of glass plate

ABSTRACT

A cheap and efficient solar water heater of about 70 litres capacity, combining collection and storage and costing less than Rs 500/-, has been fabricated. The blackened plate of the collector-cum-storage unit of this heater absorbs solar energy incident on it and transfers it to the water stored in it, the water being in direct contact with the absorber plate.

Experiments have been carried out to test the performance of the water heater under four different modes of operation, namely

a) water circulation with a small pump (0.025 hp)
b) natural convection conditions
c) water draw off taking place when the water temperature is around 50 - 60°C.
d) water flowing continuously past the absorber plate with mass flow rates of 38, 60, and 75.9 kg/h.

The day-long collection efficiency under the first two modes has been ascertained to be around 50-53% for a rise in water temperature of 50-57°C. For water

temperatures between 60-70°C, the collection efficiency is around 58-65%. No appreciable difference in the collection efficiencies has been observed under the first two modes of operation.

The average collection efficiency under the third mode of testing has been found to be 64.8% with 202.65 litre of water heated from 38.5 to 58°C.

In continuous flow of water past the absorber plate, a collection efficiency as high as 71.8% was attained at the mass flow rate of 75.9 kg/h, when tested under steady flow conditions.

If no water is drawn off during the day, temperatures between 50-60°C are reached at about 11 a.m. - 12 noon, 60-70°C at 12 noon - 1 p.m. and 70-80°C at about 1 - 2 p.m., the maximum being as high as 86°C by about 3.30 p.m.

If the temperature of water inside the collector is 74-77.5°C by the evening (about 8 p.m.), temperatures around 55-57°C are available by the next morning for use in domestic purposes.

In addition a theoretical calculation based on Hottel's equation for the overall heat loss coefficient between the absorber plate and the surroundings for the hourly rise in water temperature shows a very good agreement with the experimentally measured values of water temperatures

CHAPTER-I

INTRODUCTION

1-1 SOLAR RADIATION

The enormity of the total energy reaching the earth from the sun has attracted many individuals to the problem of considering the replacement of some of our present energy uses by solar energy. Some 800 x 10^{18} kcal of solar energy reach the earth's surface per year. Expressed in other terms, this amounts to about 32,000 times as much energy as the entire human race is currently utilizing[1].

Figure 1-1 shows the electromagnetic spectrum emitted by the sun at the outer limit of the atmosphere[2]. Ultraviolet radiation includes the wavelength range of about 0.2 to 0.4 microns; visible radiation is contained between about 0.4 to 0.7 microns; and infrared radiation occurs at the higher wavelengths. Of the total solar radiation, 9 percent occurs in the ultraviolet, 45 percent in the visible and 46 percent in the infrared region[3].

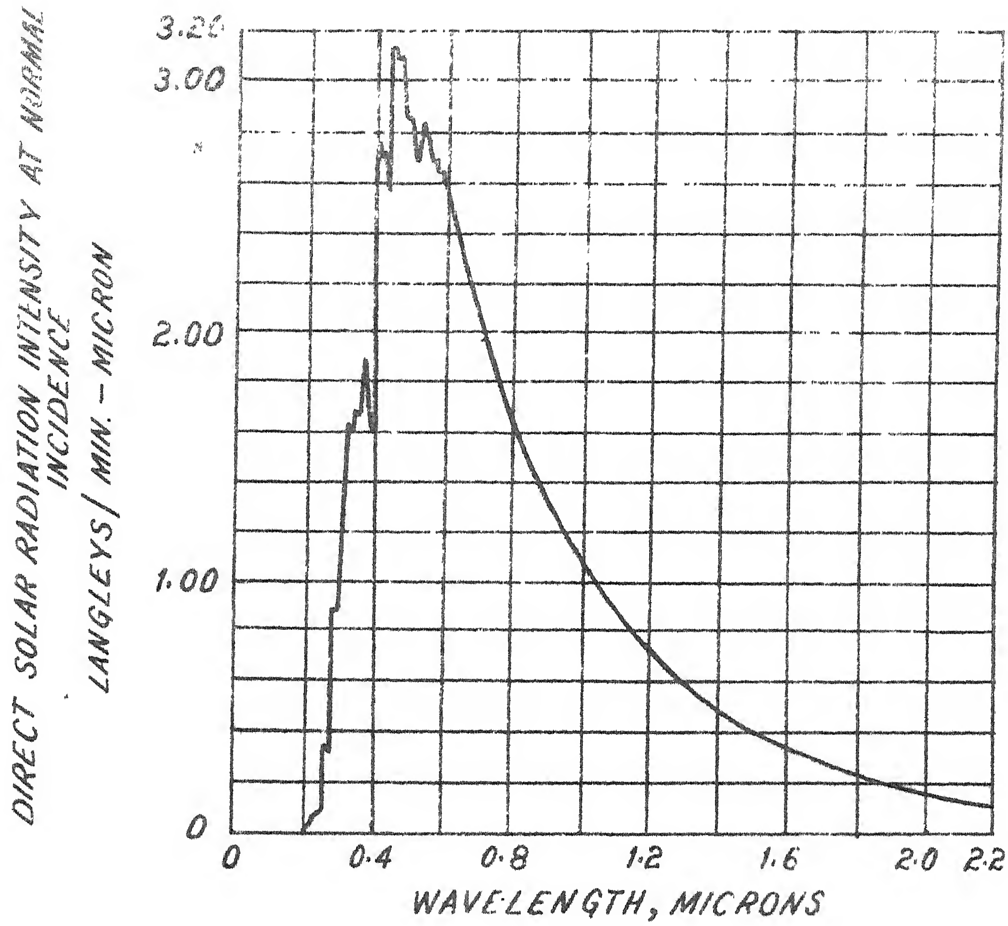

FIGURE I-1 SPECTRAL DISTRIBUTION OF SOLAR RADIATION INCIDENT UPON A SURFACE NORMAL TO THE SUN'S RAYS AT THE OUTER LIMIT OF THE ATMOSPHERE.

When the earth is at its mean distance from the sun, the amount of solar radiation which impinges on a unit area of a surface normal to the sun's rays and situated outside the atmosphere is called the solar constant. The solar constant has been determined to be 2 cal/min-cm^2, with a probable error of $\pm$ 2.0 percent[2].

Not all the energy expressed by the solar constant reaches the surface of the earth. Part of the solar radiation which is directed toward the earth is absorbed, reflectedor refracted away by the atmosphere, and the remaining portion of the original direct radiation reaches the surface of the earth.

Part of the sun's radiation after being reflected or refracted by the atmosphere is scattered and some of it from the entire sky vault reaches the earth as diffuse sky radiation.

Thus a surface on the earth receives solar energy of two forms - direct radiation and diffuse radiation.

1-2 COLLECTION OF SOLAR ENERGY

Solar energy has the advantage that it is readily available; on the other hand, its flux density is too small for many purposes. For low temperature applications of solar energy, the flat-plate collector is commonly used.

Figure 1-2 displays several flat-plate collector designs. The usual design consists of a metal plate with a black coating which has high absorptivity for solar radiation. Energy is transferred from the absorber plate to a stream of air or liquid (usually water), the sensible energy of which is then used at a remote point. The thermal efficiency of conversion of incoming sunlight to sensible energy of the fluid stream goes down as the stream mean temperature rises. The latter temperature - a measure of the magnitude of energy collected - can be raised by (a) optimizing the number of air - spaced glass cover plates which overlie the black solar absorber surface and act as an energy trap, admitting solar energy but reducing outward losses, (b) reducing convection losses, (c) improving the insulation at the back of the collector, and (d) making the black coating of the collector plate wavelength-selective.

A surface which is black, as measured by the absorption of visible radiation, and white in the far infrared is capable of absorbing sunlight effectively without losing as much energy as if it were black throughout the spectrum. Its being white at long wavelengths makes it a poor emitter of radiation. It is consequently capable of coming to a much higher equilibrium temperature than an ordinary black surface.

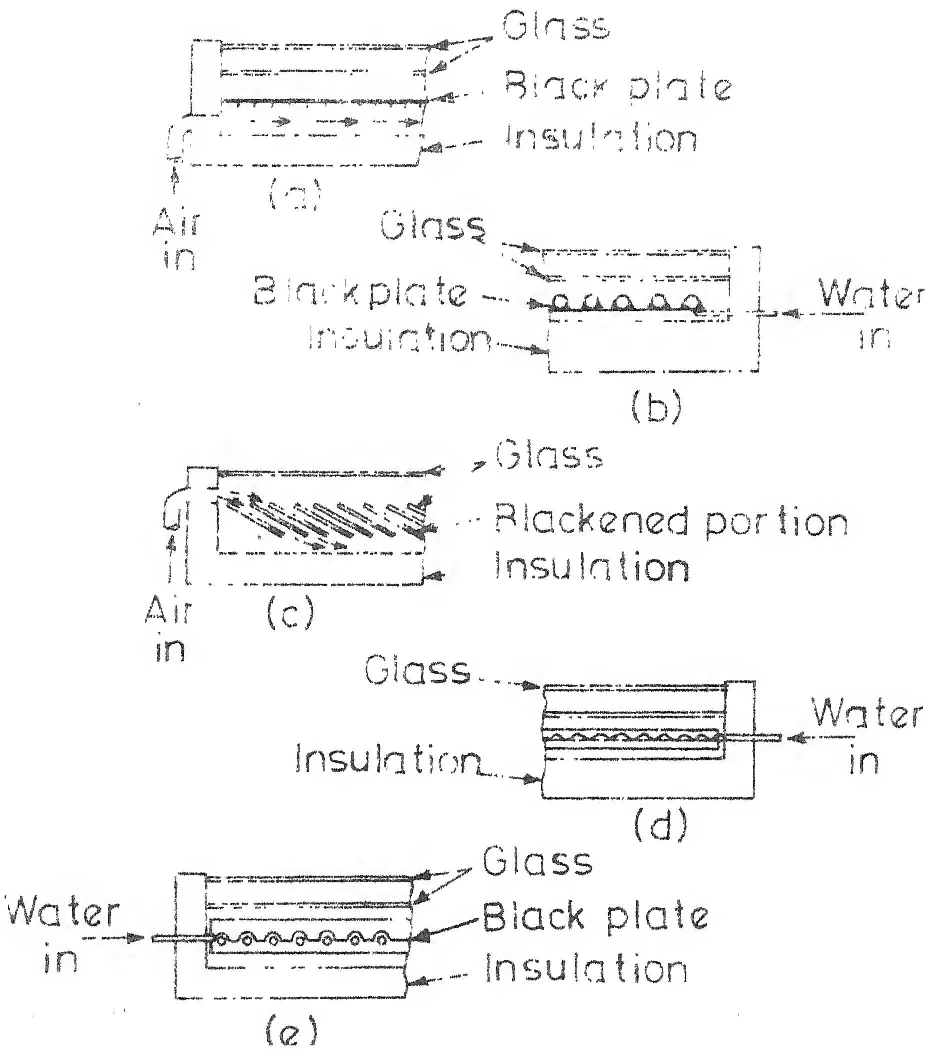

Fig 1-2 . Flat-plate collector designs.

A highly selective surface which is stable and cheap would make the flat-plate collector an important energy collecting device.

The need is for more efficient and cheaper collectors. In addition to water heating for domestic purposes, space heating by utilizing solar energy is a justifiable application now, since fossil fuels are becoming fast depleted and the cost of these concentrated fuels has also been rising at an alarming rate. Any improvements in ruggedness, reliability, efficiency, and cheapness of roof collectors will hasten the day of acceptance of solar houses.

The collector surface should be tilted to the south at such an angle that the collector surface is normal to the sun's rays at noon on the day when maximum utilization of the available sunshine is desired[4].

For high temperature applications of solar energy, collectors have to be used which concentrate the energy on the target. Parabolic reflector is generally used for this purpose. It requires direct sunlight and it must be movable in order to follow the sun. A significant fraction of the total energy from the sun is diffuse or sky radiation, not focusable and therefore lost to focusing collectors but available to flat-plate systems. This is a disadvantage of concentrating collectors.

1-3 REVIEW OF PREVIOUS WORK

Yellot and Sobotka[5] have investigated the performance of a solar water heater of the type shown in Fig. 1-2(b). The steel pipes (12 mm) are simply pressed into thermal contact with the heat absorbing plate (2.8 m^2). The heat absorbing plate has been treated by electrolytic process to produce solar radiation absorbtance as high as 0.90 and longwave emittance as low as 0.15. Two glass covers overlie this absorber plate. On a clear day (Oct. 28, 1962) the heater (inclined 38° to the horizontal) operating on thermosiphon principle collected 5,846 kcal while the total solar energy which fell on the collector area was 15, 246 kcal. Thus, the day-long (8 a.m. to 6 p.m.) efficiency of collection was about 38.5%. At noon, however, the collection efficiency was about 44%. Another aspect of the investigation by Yellot and Sobotka was to study the comparative performance of solar water heater before and after application of heat conducting cement which improved the thermal contact between the plate and the pipes. At flow rates of 44.5 and 84 kg/h (June 7, 1963), the collection efficiency was 44.3% and 45.5% respectively before using heat conducting cement. After applying heat conducting cement, the collection efficiency, for flow rates of 86 and 85 kg/h (June 12, 1963) was found to be 54% and 56.2% respectively.

The type of solar water heater shown in Fig. 1-2 (b) was also tested and analyzed by Hottel and Woertz[6]. In this heater, copper tubes are silver-soldered to a blackened copper sheet and three glass covers are used with 25 mm air spaces. The collector was inclined at 30° to the horizontal. The heater was tested under forced flow conditions and the collection efficiency ascertained was 48%.

It can be inferred from these two studies that the thermal bond between the tubes and the plate is a vital factor which determines the collection efficiency.

Another type of solar water heater shown in Fig. 1-2(d) was described by Khanna[9]. It consists of a corrugated metal sheet as the absorber backed by a plane metal sheet to form parallel water channels running the entire length of the corrugated sheet. The corrugated sheet and the plane sheet are joined together at many points by rivets. It has the disadvantage that water leaks through the rivetted joints.

Garg[7] has discussed the design of flat-plate collectors of the type shown in Fig. 1-2(e) (tube in plate type contact bond). The collector configuration of tube in plate type using various indigenous materials is optimized for maximum efficiency per unit of cost.

The collector with maximum collection efficiency was found to consist of 19 mm diameter G.I. pipes at 10 cm spacing from centre-to-centre, bonded to a 0.5 mm thick aluminium plate. Absorber areas calculated for different locations in India for 137 litres water capacity and a water temperature of 60°c are:

City	Absorber area (m^2)
Delhi	2.81
Poona	2.09
Calcutta	3.03
Madras	2.01
Roorkee	2.65

A large size solar water heater was designed, fabricated and tested for use in hospitals and hostels[8]. It heats 600 litres of water upto 55°c in the winter afternoon and gives water at 48°c to 50°c in the early mornings. On cloudy days or when the load is more than the design value, an immersion heater will be automatically switched on. The collection efficiency was about 50%. The power consumed by the pump is only 0.23 kwh per day.

Recently a solar water heater combining collection and storage has been tested in Ceylon by Chinnappa and Gnanglingam[10]. The heater consists of a square coil

of 7.5 cm diameter pipe (painted black to absorb solar energy) 13.5 m in length, encased in a wooden box with insulation at the bottom and two glass covers. The glass surface is 1.86 m^2 in area. If water is drawn off whenever the water reaches 50°c, it is possible to obtain 115-150 litres of water a day, the first draw off being made about noon. The collection efficiency based on the exposed glass area on the top of the box (which was 1.55 times larger than the horizontally projected area of the pipe surface) is around 46%.

1-4 SCOPE OF THE PRESENT WORK

The object of the present work is to fabricate a cheap, efficient, and rugged solar water heater combining collection and storage and test its performance. The unit should be sufficient to supply the energy needs for cooking, bathing, washing, and other domestic purposes of a family of five persons. The present heater has been designed for a capacity of about 70 litres.

In most of the types of the flat-plate collectors[5-8], water is made to flow through tubes in thermal contact with the blackened absorber. As the tubes (pipes) are usually separated by 7.5 cm or more of space, the temperature of the black plate between any two adjacent tubes must be several degrees higher than the temperature

of the tubes. Thus, the temperature distribution on the surface of the absorber oscillates between a maximum and a minimum along the width of the plate depending upon the number of tubes used. Since energy losses from the absorber will depend on the difference of temperature between the absorber and the surrounding air, more losses will take place from points of higher temperature difference and its efficiency may therefore be expected to be lower than that of a collector which has no tubes.

All types of solar water heaters[5-10] described so far use a storage tank to hold heated water. The storage tank is insulated from all sides to reduce energy losses. This storage tank contributes a major share in the solar water heater installation cost. The connecting pipes between the storage tank and the heater headers are an additional source of energy loss and reduce the overall collection efficiency of the installation.

In the present investigation, a cheap and efficient solar water-heater combining collection and storage has been tested. The extra cost of providing an insulated over head tank for storage has thus been eliminated.

The solar water heater under investigation is cheap since the operations involved in its fabrication are few and less time consuming. The materials used are

easily and cheaply available. The fabrication of the present solar water heater avoids the use of pipes (copper or galvanized iron) which are very expensive. As in Ref. 10 if a 7.5 cm diameter pipe is used, a heater combining collection with storage of 70 litres will require about 16.5 m of pipe length. Galvanized iron pipes of 7.5 cm diameter cost about Rs. 40/- per meter. Thus, just the cost of the pipe alone will be about Rs. 650/-. Further, this pipe will have to be in many sections, joined together by welding or elbow connections to provide 90° bends.

In earlier designs copper tubes or galvanized iron pipes were soldered to copper sheets. Copper pipes, G.I. pipes and copper sheets are all extremely expensive. Furthermore, the welding process involves an expenditure of about Rs. 12/- per meter. All these tend to increase the cost of the heater even further.

The present investigation provides a cheap and efficient unit for water heating through solar energy. In India, there is need for such a unit as the manufacturers will undertake fabrication on a large scale only if the cost of the unit inclusive of their profits is low enough to compete with an electric heater of an equivalent heating capacity.

The collection efficiency of the solar water heater under study has been found to be about 50% for water temperatures about 80-86°c. If lower temperatures (50-60°c) are desired, then the collection efficiency is about 60-70%. Temperatures between 50-60°c are obtained at about 11 a.m. - 12 noon if no water is used from the heater upto this time. However, in actual conditions of utilization , roughly 60-70 litres of hot water will be withdrawn for various purposes by 12 noon (say). An equal amount of water will flow into the heater. If no water is drawn off during the day, temperatures around 70-80°c are reached by the evening, the maximum being as high as 86°c by about 3.30 p.m. The solar water heater is covered in the evening (about 5 p.m.) to reduce night energy loss. By the next morning, the temperatures are found to be in the range 50-55°c. This hot water can be used for domestic purposes during the morning hours.

CHAPTER-II

EXPERIMENTAL SETUP

2-1 DESCRIPTION OF SOLAR WATER HEATER

A schematic diagram of the solar water heater fabricated for the present study is shown in Fig. 2-1. The details of important parts are discussed below:

Collector-cum-storage unit:

The purpose of this unit is to absorb solar energy incident on it and transfer it to the water stored in it. The enclosure (90 x 140 x 5.5 cm) which contains about 70 litres of water is built by fastening two G.I. (galvanised iron) sheets (100 x 150 x 0.15 cm) one on each side of a 5 cm thick wooden frame with nuts and bolts 7.5 x 36 mm in size. To prevent leakage of water 3 mm thick rubber gasket is placed between the sheets and the wooden frame.

To prevent the G.I. sheets from bulging under hydrostatic pressure, the sheets are bolted as shown in Fig. 2-1, with wooden spacers placed between them at six different points.

An inlet for filling the enclosure with water, an outlet to draw hot water and an air vent all made from 12 mm G.I. pipe are fitted to the container at the places shown in Fig. 2-1.

The top G.I. sheet has been cleaned with nitric acid and then three coats of black-board paint mixed with lamp black applied to make it a solar energy absorber.

Wooden box:

The collector-cum-storage unit is enclosed in a shallow box (made of chir wood) which holds it securely. The outside dimensions of the wooden box are 107 x 157 x 20.5 cm.

Glass cover:

Common window glass (104 x 154 cm, 3 mm thick) which overlies the absorber is used. The air gap between the glass cover and the absorber is 2 cm. The glass is held in a recess in the wooden box by gaskets and wooden clamping strips which permit thermal expansion but prevent the entrance of dust. Dust must be excluded since it coats the collector plate with a white film which reduces its absorptance. Glass is the most widely used material for covers because of its universal availability, low cost, and primarily because of its resistance to abrasion. Dust

is a continuous problem in many of the areas where sunshine is abundant, and it is essential that the collector be sealed tightly to prevent the entrance of even the finest sand particles. The combination of fine white dust and nocturnal dew can result in a hard white coating which must be removed mechanically. A thin layer of dust on the cover glass has only a slight effect upon the heater's performance, but moisture-bonded coatings can reduce the output quite seriously[5].

Back insulation:

To prevent energy loss through bottom of the solar water heater a layer of glass wool 10 cm thick is held between the lower plate and 12 mm plywood board screwed with the wooden box.

Top insulation:

When the local demand for hot water is primarily experienced at night, energy loss from the absorber plate to the surroundings due to radiation and convection is not very serious. In other regions, where a large morning demand exists, more attention must be paid to the solar water heater insulation.

Single glazing is not effective to check night energy loss from the top of the collector so that water

temperatures by morning fall below 50-55°C, if extra insulation is not provided over the glass.

A separate insulation cover has been made to reduce night energy loss. A layer of glass wool 5 cm thick is enclosed in a shallow 1.5 mm plywood casing. The outside dimensions of this cover are 110 x 160 x 5.3 cm. This cover is light enough so that one person can easily place it on the solar water heater in the evening (at about 5 p.m.). The solar water heater should be uncovered the next morning to let the solar radiation fall on the absorber plate.

Pipe fittings:

To test the solar water heater under various modes (see sec. 2-3) the pipe connections have been made as shown in Fig. 2-2(a). All fittings are 12 mm in size. The water inside the collector is circulated by a small pump (0.025 hp) to mix it thoroughly so that average water temperatures can be measured.

A photographic view of the apparatus is shown in Fig. 2-3.

2-2 EXPERIMENTAL DATA

The data taken for determining the flat-plate collector-cum-storage performance included the following:

(a) Total Solar Radiation (Global radiation)

This includes both the direct and sky radiation. An instrument suitable for the measurement of the global and sky radiation is called pyranometer. An Eppley pyranometer was used to measure the total radiation on a horizontal surface. The receiving surface of the Eppley pyranometer consists of two concentric silver rings ; the inner one is coated black (Parson's optical black lacquer) and the outer one is coated with white (magnesium oxide). The temperature difference between the two rings is measured with thermojunctions, which are in good thermal contact with the lower surfaces of the ring but are, of course, electrically insulated from them. The whole assembly is hermetically sealed inside a specially blown spherical lamp bulb filled with dry air. The magnesium oxide is a good reflector of solar radiation but is a strong absorber of long-wave radiation from the glass envelope.

(b) Fraction of total radiation arriving as diffuse or sky radiation. This is based on results of occasionally shading the pyranometer from the sun and observing the lowest radiation indicated.

The ratio of the sky radiation to the global radiation fluctuates markedly, being unity when the sky

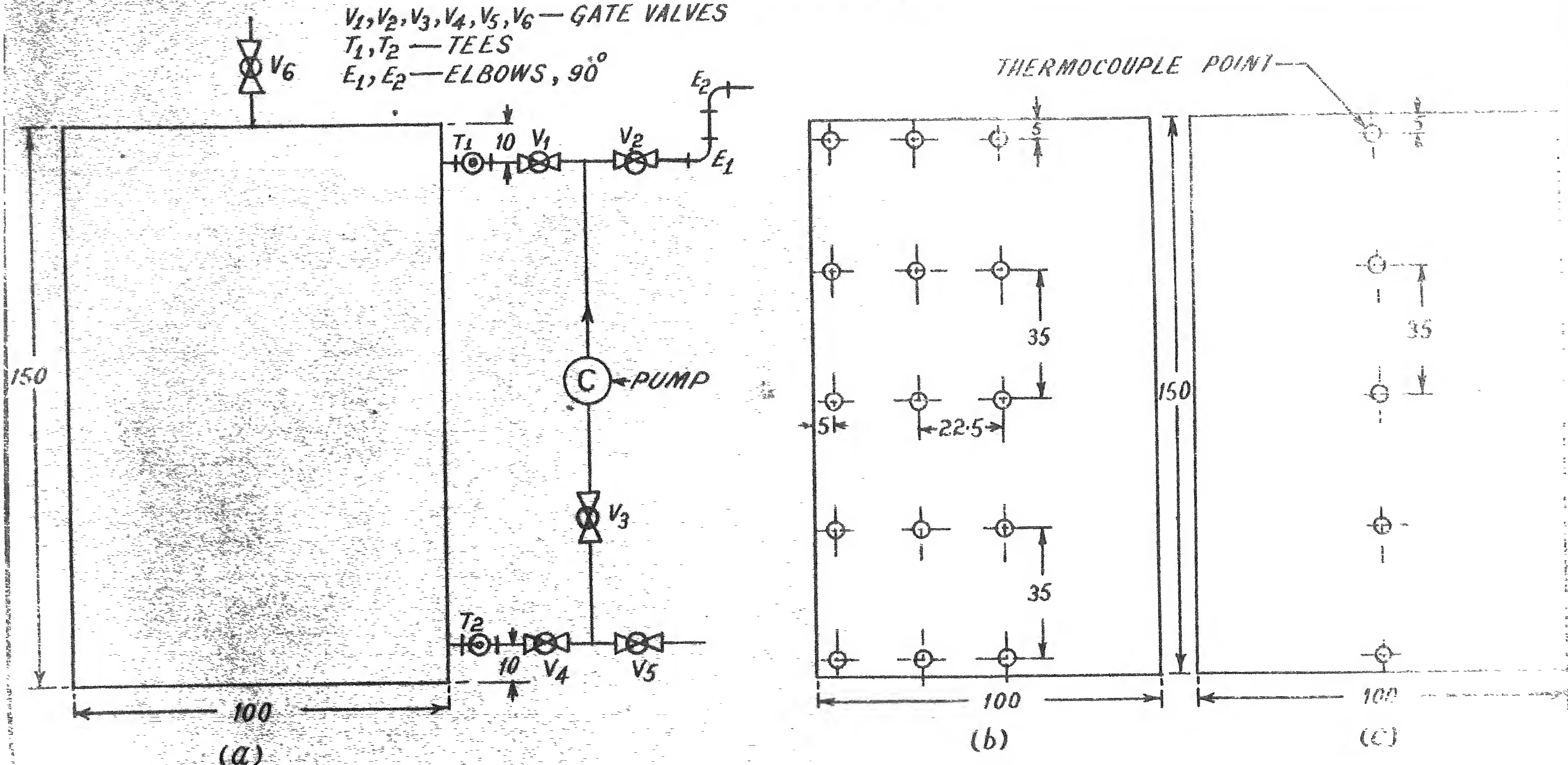

FIGURE 2-2. PIPE FITTINGS TO THE COLLECTOR-CUM-STORAGE UNIT AND THERMOCOUPLE POINTS ON THE ABSORBER AND THE BACK PLATES

ALL DIMENSIONS IN Cm

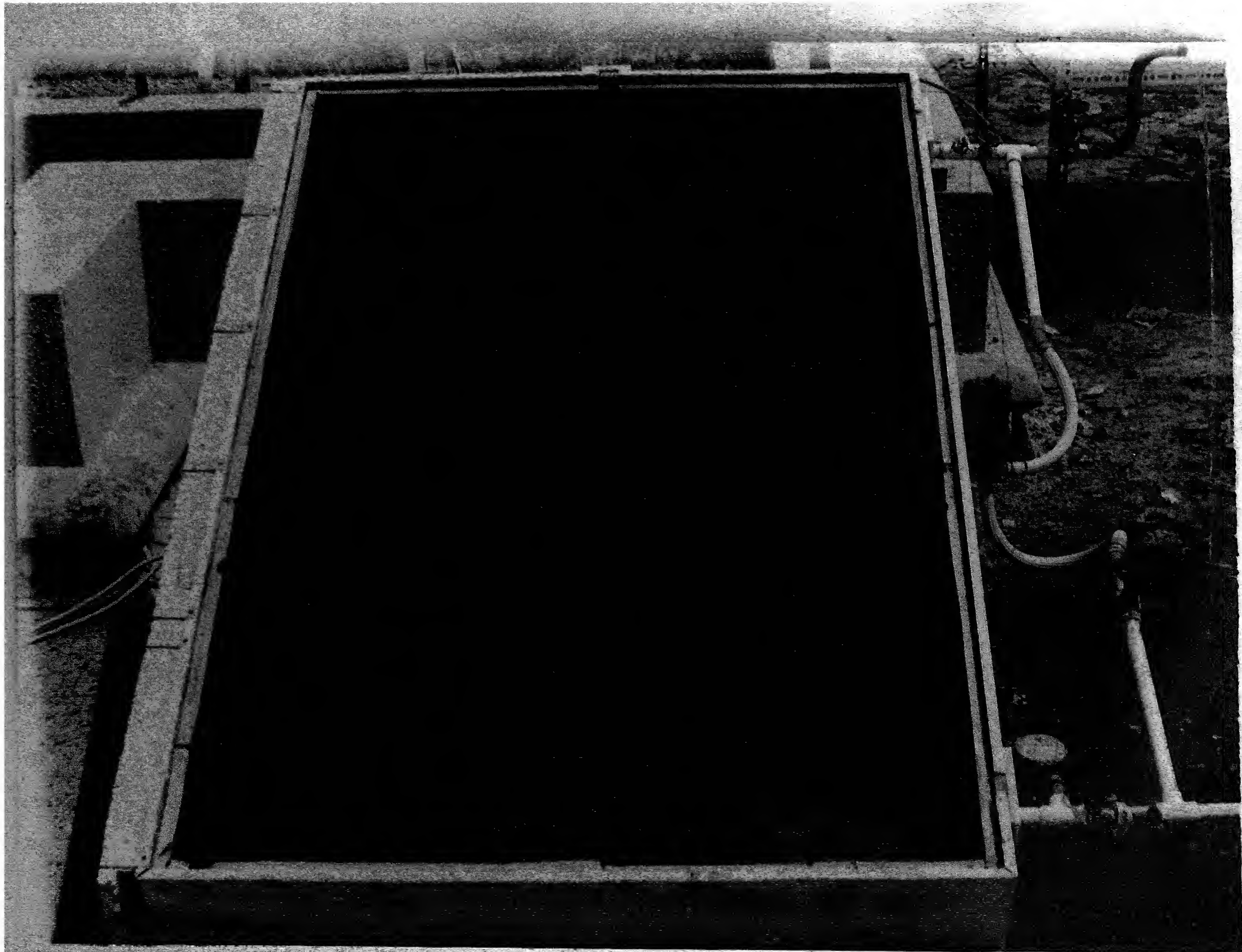

Fig. 2-3 A photographic view of the experimental apparatus (with glass cover removed)

is densely overcast but falling below 0.1 in extremely clear conditions.

A Leads and Northrup millivolt recorder was used to record continuously the global radiation.

(c) Temperature Measurements

All temperatures except the ambient were measured with caliberated copper-constantan (24 gauge wire) teflon-insulated thermocouples. Fifteen thermocouples were soldered to the absorber plate and five to the lower plate at positions shown in Fig. 2-2(b) and (c).

Ambient temperatures were measured with a thermometer placed in shade and having least count of 0.1°C.

Average water temperatures were measured by a copper-constantan thermocouple which remained dipped in water contained in the collector-cum-storage unit.

In continuous flow condition, the difference in the outlet and the inlet water temperatures was measured by a differential copper-constantan thermocouple.

(d) Wind Direction and Velocity

A windscope was used to measure both the direction and velocity of the wind. The windscope has a vane and revolving cups mounted in suitable positions.

Depending on the direction of the vane and speed of the revolving cups, indications are obtained on an instrument connected through a cable to the windscope.

2-3 MODES OF TESTS

The solar water heater was tested under four different modes of operation. In the first mode the water in the collector-cum-storage unit was circulated with a small pump (0.025 hp) and allowed to reach the highest possible temperature. The net energy input by the pump being small as compared to the total useful energy (425 - 500 kcal/h) has been neglected.

In the second mode of testing the collector-cum-storage unit was filled with water in the morning and was allowed to reach the highest possible temperature (which it did at about 3-4 p.m.) under natural convection conditions.

In the third mode, the water was drawn off as soon as the temperature reached 50-60°C. Then a fresh charge of water was introduced. The number of such draw - offs was noted.

In the fourth mode of testing, water was made to flow past the absorber plate continuously at one fixed

flow rate throughout the day. Three such tests with mass flux densities of 25.3, 40, and 50 kg/h - m^2 were conducted.

The experimental data and results of tests under different modes of operation are presented in the next Chapter.

CHAPTER-III

ANALYSIS OF EXPERIMENTAL DATA

3-1 SOLAR ENERGY INPUT

Let H = instantaneous rate of incidence of total radiation on a horizontal surface obtained with an Eppley pyranometer, Langleys/min.

$$= H_D + H_S \quad \ldots \qquad (3-1)$$

where H_D is the direct component of radiation and H_S is the diffuse component of radiation[11].

H_T = instantaneous rate of incidence of total radiation falling on the cover plate of the collector.

$$= H_D R_D + H_S R_S \quad \ldots \qquad (3-2)$$

where R_D and R_S are orientation factors to convert horizontal incidence to incidence on tilted collector surface for direct and diffuse components of solar radiation respectively.

$$R_D = \cos \theta_T / \cos \theta_H \quad \ldots \quad (3\text{-}3)$$

where θ_T and θ_H are angles of incidence of direct sunlight on a tilted and a horizontal surface, respectively.

$$\cos \theta_T = \sin (l - b) \sin d + \cos (l - b) \cos d \cos h \quad (3\text{-}4)$$

$$\cos \theta_H = \sin l \sin d + \cos l \cos d \cos h \quad \ldots . \quad (3\text{-}5)$$

l = latitude of place (26° - 26')

b = tilt angle of the collector with the horizontal

h = hour angle from noon (15 degrees per hour)

d = declination of sun, the angular distance of the sun's rays north (or south) of the equator. It is the angle between a line extending from the centre of the sun to the centre of the earth and the projection of this line upon the earth's equatorial plane[2].

$$R_S = (1 + \cos b) / 2 \quad \ldots \quad (3\text{-}6)$$

A computer programme has been written (see Appendix-A) to convert the instantaneous solar flux density

on a horizontal surface to the instantaneous value on the tilted surface of the collector using Eqs. (3-1) to (3-6).

3-2 RESULTS AND DISCUSSION

The experimental phase of this study consisted of tests conducted during March, April, and May, 1974. During the test period, a wide range of climatic conditions was encountered, with variations of wind velocity, ambient temperature and most important of all, solar radiation intensity.

Relevant data and results of tests with water circulation and natural convection conditions are summarized in Table 3-1. The variation of direct solar radiation H_D , diffuse sky radiation H_S incident upon an unshaded horizontal surface, solar flux density (Langleys/min) H_T incident on the tilted collector surface on March 9 and March 31, 1974 are shown in Figs. 3-1 and 3-2 respectively which also show the variation in the water and the ambient temperatures.

Water temperatures about 50-60°C are reached at about 11 a.m. - 12 noon, 60-70°C at 12 noon - 1 p.m. and 70-80°C at about 1 - 2 p.m. The maximum water temperature ever attained was 86°C on March 31, 1974 at 3.30 p.m. when the ambient temperature was 35°C and the wind velocity was 14.5 km/h.

Table 3-1 : Results of tests with water circulation and natural convection conditions

Mode of test	Date (1974)	Water Temperatures (°C) Initial	Final	Time From a.m	To p.m.	Tilt angle deg.	Total insolation (kcal)	Total energy collected (kcal)	Percent collection efficiency
Water circulated with pump	5 March	25.75	82.0	8.20	3.30	37	7800.30	3900.00	50.00
	7 March	29.00	83.1	8.30	3.30	37	7353.00	3750.00	51.00
"	9 March	26.5	76.5	8.00	3.00	37	7012.80	3460.00	49.40
"	31 March	29.0	86.0	8.00	3.00	30	7827.75	3943.00	50.25
Natural convection	1 April	34.0	84.0	8.15	3.15	30	6541.40	3460.00	53.00
	3 April	25.8	71.0	7.30	1.45	30	5374.35	3130.00	58.30
"	5 April	26.0	82.5	7.30	3.30	25	7639.20	3910.00	51.25

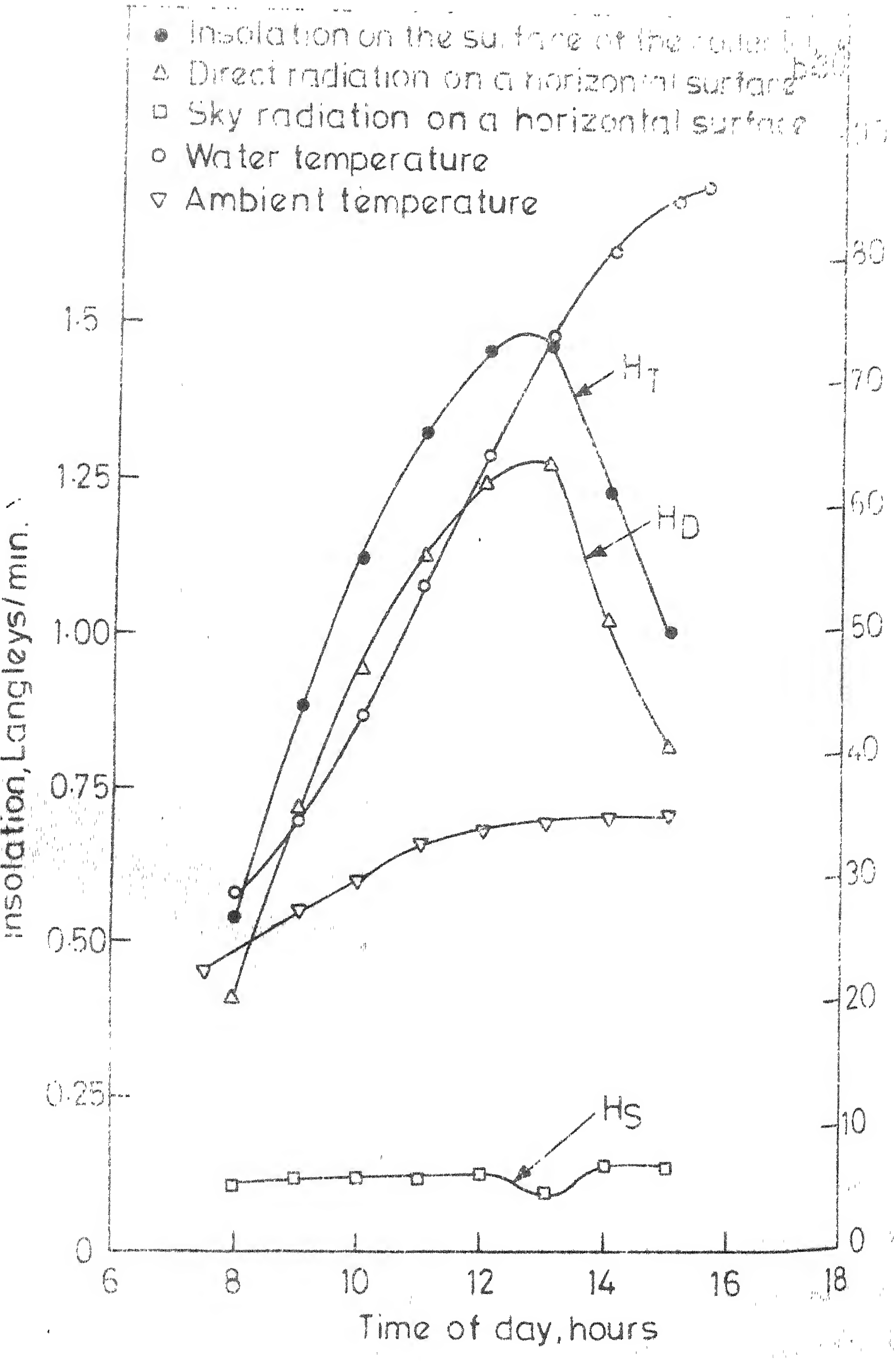

Fig 3-2 · Experimental results for test at Kanpur, 31 March 1974.

Figures 3-1 and 3-2 show that the rate of rise of water temperature is slow in the early morning hours. At about 9 a.m. the rate of temperature rise increases somewhat and remains almost constant until 1-2 p.m. and afterwards it starts decreasing continuously and is almost zero for some interval of time between 3-4 p.m. During this interval the energy losses from the collector just balance the solar energy input. After this interval the difference between the energy loss from the collector and the solar energy input continuously increases until sunset. Later the rate of energy loss from the collector will further increase and thus water temperature will start falling more rapidly depending upon the type and amount of insulation at the back and the top of the collector.

Water temperature of about 50°C is needed for domestic use. This is reached at about 11 a.m. when the solar water heater is filled in the morning at about 8 a.m. In a domestic installation water will not be withdrawn precisely at the times when the water reaches a predetermined temperature (50 - 55°C). It is also unlikely that water is withdrawn only until the maximum temperature is reached at about 3-4 p.m. However, if water at a temperature greater than 50 - 55°C is drawn off, then it will be necessary to mix the hot water with cold water

to obtain the desired temperature and this would be approximately equivalent to drawing off water at about 50 - 55°C.

It was therefore felt that the third mode of testing in which the amount of water which could be raised to 50 - 60°C over the day is assessed, would be a fair indication of performance of this heater.

Experimental data and results for such a test are shown in Fig. 3-3 and Table 3-2. On the average 202.65 litres of water could be heated from 38.5°C to 58.0°C in about 7.5 hours.

The aim of these tests is also to ascertain the collection efficiency based on the glazed area (1.5 m^2) exposed to sun. The collection efficiency is defined as the ratio of utilized energy to the solar energy incident normally on the cover plate. With water circulation and in natural convection conditions, it has been found that for a rise in water temperature of 50 - 57°C, the collection efficiency is around 50 - 53%. Under conditions of utilization, where the water temperature does not exceed 60°C, the collection efficiency will be rather higher as is evident from Table 3-2.

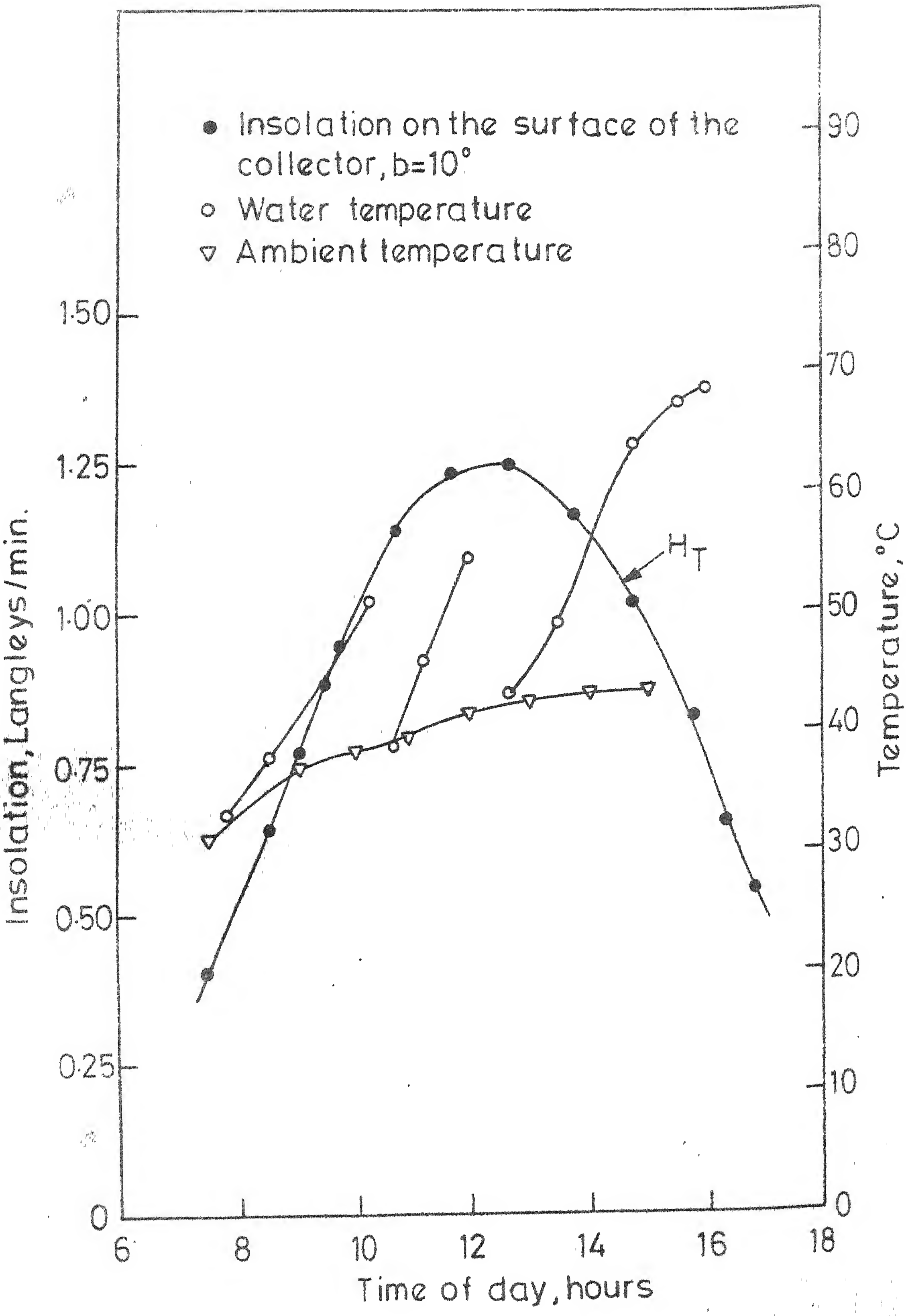

Fig. 3-3. Experimental results for test at Kanpur, 26 April 1974.

Table 3-2 : Results of tests with draw offs (April 26, 1974), b = 10°

Time		Water temperature (°C)		Hot water drawn off (kg)	Total heat collected (kcal)	Total insolation (kcal)	Percent collection efficiency
From	To	Initial	Final				
7.50 a.m.	10.15 a.m.	33.3	51.0	66.725	1180	1671	70.7
10.45 a.m.	12.00 noon	39.0	54.5	66.725	1032	1335	77.6
12.40 p.m.	4.00 p.m.	43.3	68.4	69.2	1738	3096	56.2
		33.53 (Average)	58.0 (Average)	202.65 (Total)	3950 (Total)	6102 (Total)	64.8 (Average)

Tests with continuous flow of water through the heater were also conducted. Experimental results and data for three such tests with mass flux densities of 25.3, 40, and 50 kg/h-m^2 conducted on April 27, 28 and May 1, 1974 respectively are shown in Figs. 3-4,3-5 3-6 and Table 3-3. There is a considerable improvement in the collection efficiency but the temperature of the outgoing water will be correspondingly lower. Figures 3-4, 3-5, and 3-6 show that the outlet water temperature of 50°C is reached at about 10 a.m. and that it is always higher than 50°C until 4-5 p.m.

Overcast sky greatly influences the performance characteristics and produces a saddle-shaped dip (Fig.3-5).

Maximum collection efficiency (71.8%) is achieved with a mass flow rate of 75.9 kg/h when the increase in internal energy of water inside the collector is negligible (12.45 kcal/h).

With water flowing past the absorber plate, the heat balance equation for the collector can be written as:

Energy absorbed by the absorber plate	=	energy utilized by flowing water	+	increase in the internal energy of water inside the collector.	+	energy losses from the collector.

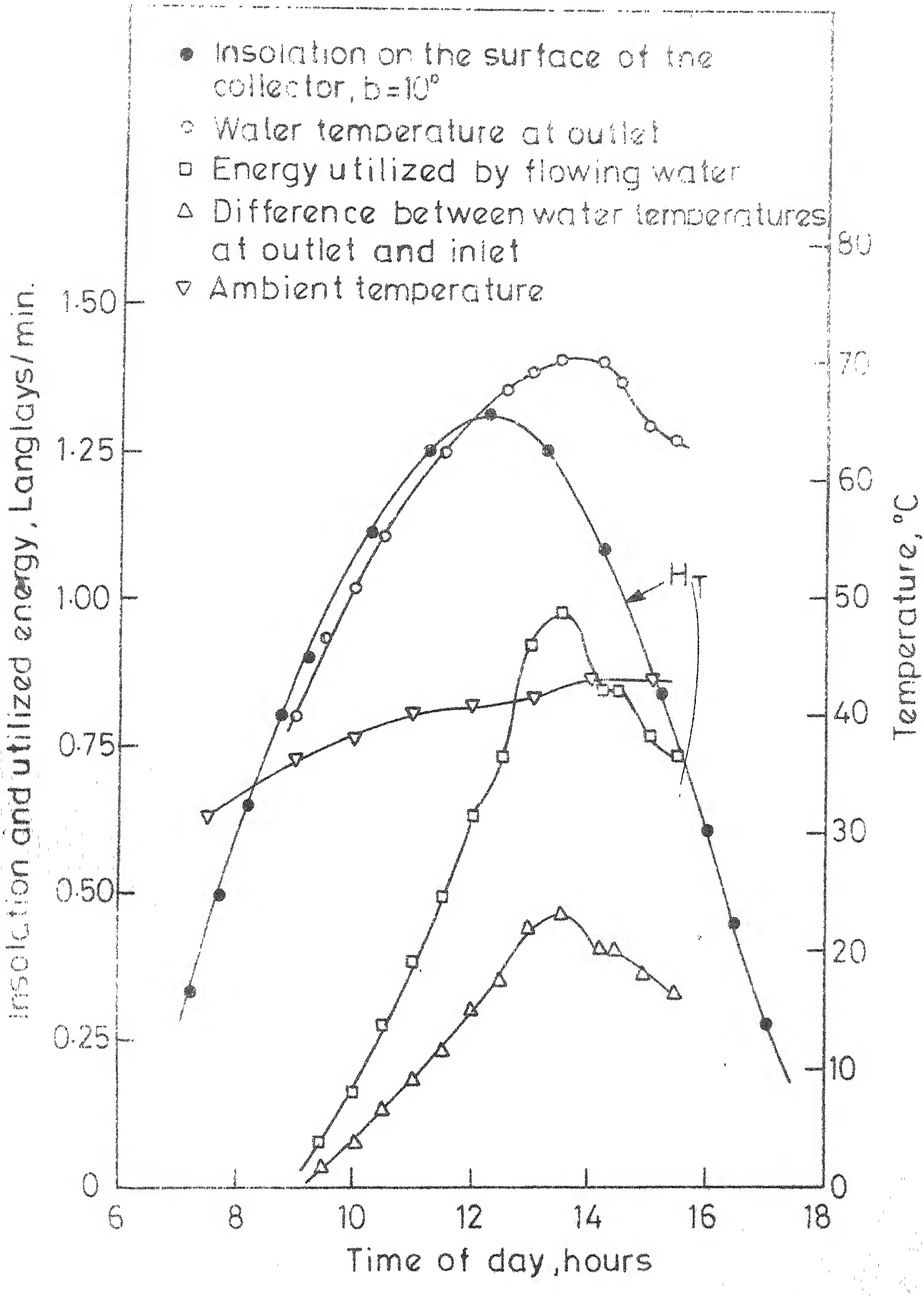

Fig. 3-4 · Experimental results for test at Kanpur, 27 April, 197

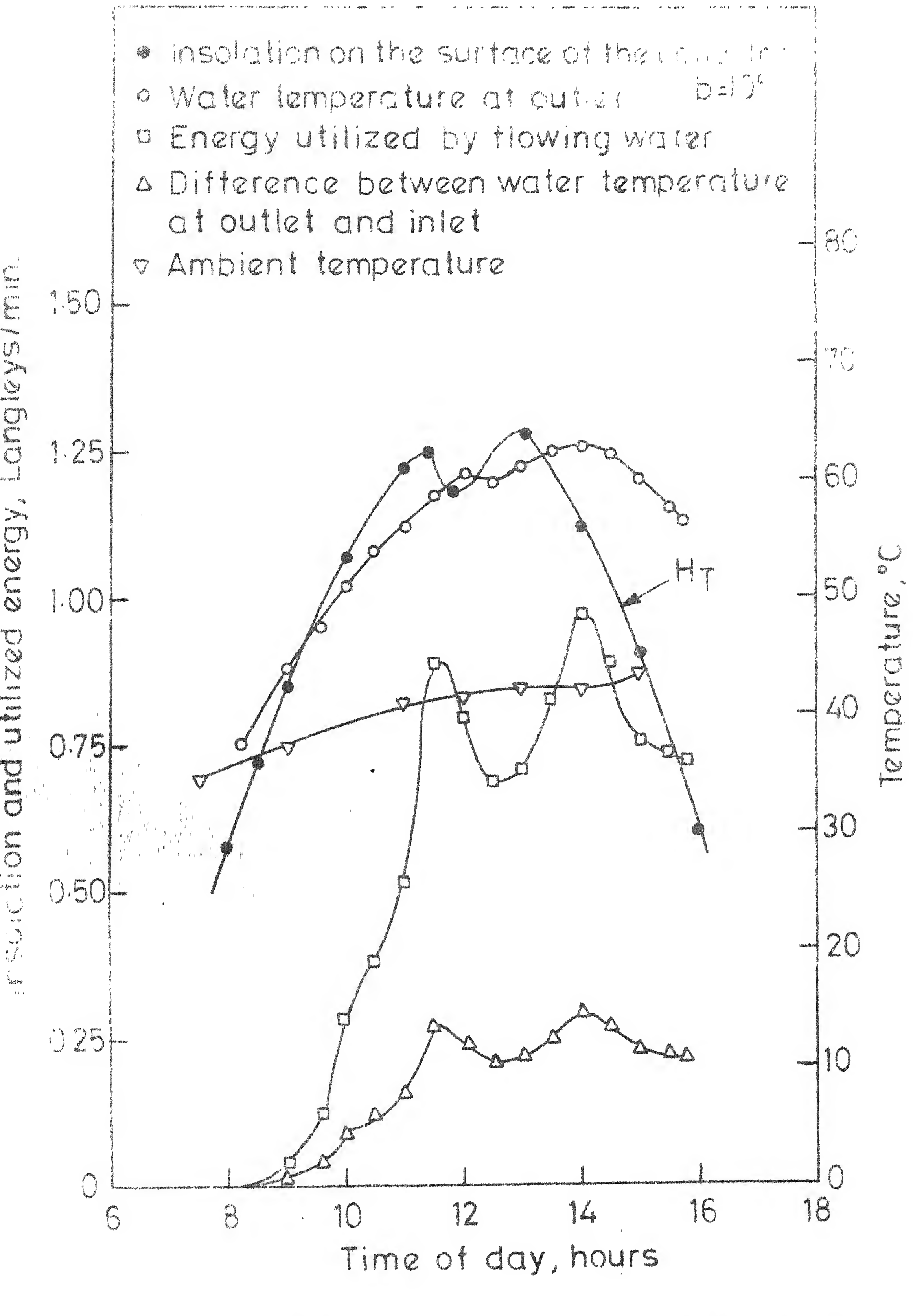

Fig.3-5 · Experimental results for test at Kanpur, 28 April 1974.

Table 3-3 : Experimental data and results of tests in continuous flow

Test No.	Date (1974)	Time		Tilt angle deg.	Mass flow rate (kg/h)	Energy utilized by flowing water (kcal)	Temperature of water inside the collector (°C)		Increase in the internal energy of water inside the collector (kcal)	Solar energy input (kcal)	Total utilized energy (kcal)	Percent collector efficiency.
		From (a.m.)	To (p.m.)				Initial	Final				
1	27 April	9.00	4.00	10	38.0	3414.6	39.8	57.0	1184.0	6871.5	4598.6	67.0
2	28 April	8.15	4.00	10	60.0	3834.0	37.4	51.65	980.0	7277.8	4814.0	66.4
3	1 May	9.20	4.00	10	75.9	4505.85	48.0	49.2	83.0	6386.4	4588.8	71.8

Assuming steady temperature and flow conditions (the absorber plate remains at a constant temperature and the temperatures as well as flow rates of water are invariant in time) the energy balance equation can be written as

$$H_T\ (\tau\alpha) = \dot{m}\ c_p(t_2 - t_1) + U\ (t_p - t_a) \qquad (3\text{-}7)$$

where τ is the transmissivity of the glass cover

α is the absorptivity of the absorber plate

$\dot{m}$ is the mass flux ~~density~~ of water

c_p is the specific heat of water

t_2, t_1 are the outlet and the inlet water temperatures respectively

t_p, t_a are the absorber plate and the ambient temperatures respectively, and

U is the overall heat loss coefficient for the collector.

The overall collector heat loss coefficient is defined as[13]

$$U = q_l\ /\ (t_p - t_a) \quad \ldots \qquad (3\text{-}8)$$

where q_l = total energy loss per unit surface of the collector

t_p = absorber plate temperature

t_a = ambient temperature.

Knowing the incident radiation H_T and the mass

flow rate $\dot{m}$, the value of overall collector heat loss coefficient can be found from Eq. (3-7).

3-3 PERFORMANCE EQUATIONS AND FURTHER DISCUSSION

The energy loss q_l from the collector can be written as

$$q_l = q_b + q_{pgr} + q_{pgc} \quad \ldots \tag{3-9}$$

where q_b is the energy exchange between the back (lower) plate of the collector and the surroundings

q_{pgr} is the energy exchange between the blackened plate and the glass cover by radiation, and

q_{pgc} is the energy exchange between the absorber (blackened) plate and the glass cover by convection.

The values of q_b , q_{pgr} and q_{pgc} are

$$q_b = U_B\,(t_b - t_a) \quad \ldots \tag{3-10}$$

$$q_{pgr} = \sigma\,(T_p^4 - T_g^4)\ /\ (1/\epsilon_p + 1/\epsilon_g - 1) \tag{3-11}$$

$$q_{pgc} = c\,(t_p - t_g)^{5/4} \quad \ldots \tag{3-12}$$

where U_B is the overall heat transfer coefficient between the back (lower) plate and the surroundings

t_b is the back (lower) plate temperature

T_p , T_g the absolute temperatures of the absorber plate and the glass cover respectively and

ϵ_p , ϵ_g the emissivities of the absorber and the glass plates respectively.

The values of the convection coefficient c have been found experimentally to be 1.41, 1.13, and 1.02 kcal/m^2-h -($°K$)$^{5/4}$ for angles of 0 , 45 , and 90° from the horizontal[13].

The glass cover exchanges energy by radiation and convection to the surrounding air

$$q_{gor} = \sigma \epsilon_g (T_g^4 - T_s^4) \quad . \; . \; . \qquad (3\text{-}13)$$

$$q_{goc} = h (t_g - t_a) \quad . \; . \; . \qquad (3\text{-}14)$$

where q_{gor} is the radiation exchange between the glass cover and the surroundings whose equivalent temperature is T_s and

q_{goc} is the convection energy exchange between the glass cover and the surrounding air.

The heat transfer coefficient h for wind velocities of 0, 16.1, and 32.2 km/h is 4.882, 20.0, and 34.2 kcal/m^2-h-$°K$[13].

Assuming that glass cover has negligible thermal capacity

$$q_u = q_{pgc} + q_{pgr} = q_{goc} + q_{gor} \qquad (3\text{-}15)$$

where q_u is the upward energy exchange between the absorber plate and the surroundings.

Since it is easy and economical to provide good insulation, the energy loss from the back of the collector is negligible as compared to the upward energy loss from the absorber plate to the surroundings. An example of this situation will be presented shortly.

It is worthwhile to consider glass properties at this point. Glass is capable of transmitting solar radiation and for practical purposes, opaque to the long-wave-length thermal radiation.

Figure 3-7(a) shows the transmission curves for two thicknesses of glass (radiation at normal incidence) each containing 0.035 Fe_2O_2[14]. Since the solar spectrum extends from about 0.3 - 2.3 μ, Fig. 3-7(a) shows that low-iron glass has an essentially constant transmissivity over the entire solar spectrum.

Transmission curves for a system of glass plates, allowing for reflection losses only are shown in Fig. 3-7 (b)[14]. Transmissivity of glass for solar radiation is little affected by angles of incidence for angles less than about 50 degrees. For higher angles the fall in transmission is quite rapid. Even at normal incidence roughly 4% of solar radiation is reflected at each surface

of ordinary glass, giving a theoretical maximum of 92% transmission for a single glass with zero absorption[15].

In the calculations that follow values of

transmissivity of glass plate τ = 0.9

absorptivity of blackened plate α = 0.95

emissivity of glass plate ϵ_g = 0.96 and

emissivity of blackened plate ϵ_p = 0.95

have been assumed[12].

For an hourly interval of time, suffixes 1 and 2 denote values at the start and end of the interval.

The overall energy transfer coefficient from the collector surface rearwards through insulation to outside air,

$$U_B = k_c/d_c = 0.32 \text{ kcal/m}^2\text{-h-°C} \qquad \ldots \qquad (3.16)$$

where k_c is the thermal conductivity of glass wool insulation and is equal to 0.032 kcal/m-h-°C and d_c is thickness of insulation, 0.1 m.

The back plate temperature has been assumed to be equal to the arithmetic mean of water temperatures t_{wc1} and t_{wc2} thus

$$t_b = 1/2\ (t_{wc2} + t_{wc1}) \qquad \ldots \qquad (3\text{-}17)$$

A computer programme (see Appendix-B) has been devised to calculate q_u and q_b using Eqs. (3-9) to (3-17)

and assumed values of τ, α, ϵ_p and ϵ_g.

The calculations have been made for one day (March 31, 1974) using data given in Table 3-4 and Fig. 3-2. The computed values of q_u and q_b are shown in Table 3-5. The inclination angle of the collector with the horizontal on March 31, 1974 was 30 degrees. Therefore the convection coefficient (see page 42) $c = 1.33$ kcal/m^2-h-($^\circ$K)$^{5/4}$. The average wind velocity was 11.7 km/h and the corresponding value of heat transfer coefficient (see page 42) h is 15.85 kcal/m^2-h-$^\circ$K.

From Table 3-5, it is evident that the energy loss from the back of the collector q_b is only 59.45/1574.9 = 0.038 times the upward energy losses q_u and therefore, may be neglected. However, q_b can be further reduced by providing extra insulation layer which may not increase the cost of the solar water heater significantly.

q_a = hourly rate of absorption of solar radiation by collector per unit of surface

$= H_T\ (\tau\alpha)$ . . . (3-18)

A_c = 1.5m^2, area of collector surface

m = 69.2 kg , the total mass of water in the collector-cum-storage unit

Table 3-4 : Experimental data for test on solar water heater (March 31, 1974)

Time	8 a.m.	9 a.m.	10 a.m.	11 a.m.	12 noon	1 p.m.	2 p.m.	3 p.m.
water temperature (°C)	29.0	34.8	43.3	53.8	64.5	74.0	81.0	85.0
Ambient temperature (°C)	24.3	27.2	29.7	32.8	34.0	34.5	34.8	35.0
Absorber plate Temperature (°C)	30.3	37.6	47.76	58.55	69.28	77.88	83.10	86.0

Table 3-5 : Calculated energy losses from the collector (March 31, 1974)

Time		q_{pgr}	q_{pgc}	q_{gor}	q_{goc}	q_u	q_b
From	To	kcal/m^2-h					
8 a.m.	9 a.m.	65.45	27.35	27.6	66.0	92.6	1.97
9 a.m.	10 a.m.	78.70	31.20	34.1	75.9	109.7	3.40
10 a.m.	11 a.m.	96.60	36.0	43.4	89.1	132.3	5.53
11 a.m.	12 noon	151.50	58.2	68.9	140.8	209.1	8.25
12 noon	1 p.m.	219.15	87.1	99.0	207.9	305.6	11.20
1 p.m.	2 p.m.	255.5	99.7	116.0	239.8	354.6	13.70
2 p.m.	3 p.m.	269.0	102.0	123.9	248.6	371.0	15.40
						1574.9 (Total)	59.45 (Total)

q_w = hourly rate of useful energy collection per unit of collector surface

$$=(m/A_c)(t_{wc2} - t_{wc1}) \quad \ldots \quad (3\text{-}19)$$

Under conditions of unsteady flow, the rate of absorption of solar radiation is equal to the sum of the rate of increase in the internal energy of water and the rate of energy loss from the apparatus. For hourly intervals of time, this equation can be written as :

$$q_a = q_w + U\,(t_{pav} - t_{aav}) \quad \ldots \quad (3\text{-}20)$$

where t_{pav} = average absorber plate temperature

$$= (t_{p2} + t_{p1})/2$$

t_{aav} = average ambient temperature

$$= (t_{a2} + t_{a1})/2$$

$$U = U_L + U_B$$

where U_L = overall heat transfer coefficient from the collector surface upward through glass plate to ambient air. From Hottel and Woertz[6]

$$U_L = \frac{1}{\dfrac{n}{c\,\dfrac{(T_p - T_a)^{1/4}}{(n+f)^{1/4}}} + \dfrac{1}{h}}$$

$$+ \frac{\sigma\,(T_p^4 - T_a^4)}{\left[\dfrac{1}{\epsilon_p} + \dfrac{2n + f - 1}{\epsilon_g} - n\right](T_p - T_a)} \quad (3\text{-}21)$$

where n = number of glass plates = 1

c = convection coefficient (see page 42)

h = heat transfer coefficient depending upon wind velocity (see page 42)

f = 0.76, 0.36, and 0.24 for wind velocities of 0, 16.1, and 32.2 km/h

$\sigma = 4.9 \times 10^{-8}$ kcal/m^2-h-(°K)^4.

Using Eqs. (3-18) to (3-21), and the data given in Tables (3-4) and (3-6), it is possible to predict the hourly temperature rise of water. (see Table 3-6). The experimental and the calculated hourly values of water temperatures are plotted in Fig. 3-8, which shows that the calculated values are very close to the experimentally measured values.

The energy losses from the collector until 12 noon or even 1 p.m. are reasonable (Table 3-5) to be acceptable (the collection efficiency between 8 a.m. and 12 noon is 64% and between 8 a.m. and 1 p.m. is 60.2%). But after 1 p.m. , the upward energy losses increase very much. From Table 3-5, the upward energy loss between 2-3 p.m. is 371 kcal/m^2 whereas the total absorbed energy is 570.9 kcal/m^2. Therefore, additional insulation at the top of the solar water heater is essential if the hot water inside the collector is to be stored for use in morning hours.

Table 3-6 : Experimental data and calculated results for test on solar water heater (March 31, 1974)

Time From	Time To	Insolation H_T $\frac{kcal}{m^2\text{-}h}$	Energy absorbed by q_a $\frac{kcal}{m^2\text{-}h}$	Useful energy q_w $\frac{kcal}{m^2\text{-}h}$	Experimental U $\frac{kcal}{m^2\text{-}h\text{-}°C}$	Calculated U $\frac{kcal}{m^2\text{-}h\text{-}°C}$	Experimental, hourly rise in water temp. (°C)	Calculated hourly rise in water temp. (°C)
8 a.m.	9 a.m.	423.6	362.2	267.6	11.5	5.6	5.8	6.85
9 a.m.	10 a.m.	591.0	505.3	392.0	7.95	6.0	8.5	9.10
10 a.m.	11 a.m.	727.8	622.3	484.0	6.30	6.5	10.5	10.40
11 a.m.	12 noon	831.6	711.0	493.6	7.10	6.87	10.7	10.85
12 noon	1 p.m.	883.2	755.15	438.3	7.98	7.22	9.5	10.20
1 p.m.	2 p.m.	808.5	691.3	323.0	8.05	7.45	7.0	7.57
2 p.m.	3 p.m.	667.8	570.9	184.5	7.80	7.60	4.0	4.21

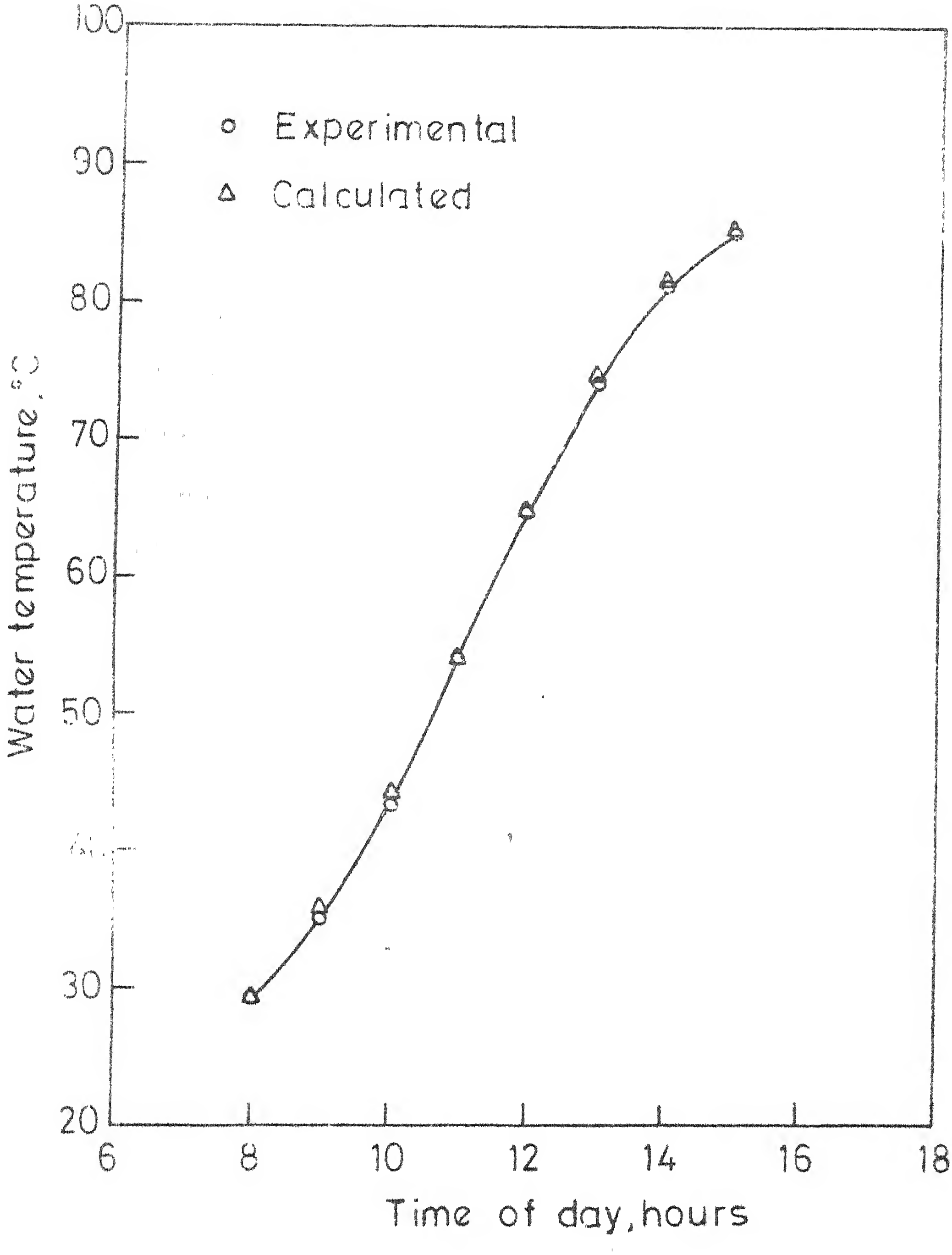

Fig. 3-8 · Comparison of experimental and calculated values of water temperature (March 31, 1974)

Chinnappa and Gnanglingam[10] have studied the energy storage characteristics of solar water heater with single and double cover plates of glass. They have reported that the rate of energy loss with double cover is about one half the value with one cover.

To reduce night losses from the collector, so that water temperatures by morning are within reasonable limits for domestic use, an additional insulation cover filled with glass wool (see section 2-1) has been made. The energy storage characteristics of the present heater with and without the additional insulation cover are shown in Table 3-7.

With one glass cover, the temperatures obtained in the early morning are about 38-39°C whereas with the additional insulation cover, the temperatures are around 55-57°C. These temperatures are quite satisfactory for domestic uses.

Table 3-7 : Energy storage characteristics

	Date	Time	Ambient temp. (°C)	Water temp. (°C)	
	25.4.74	3.30p.m.	43.2	81.0	Drop in temperature
		6.15p.m.	38.9	72.1	between 6.15 p.m.
		10.45p.m.	31.3	54.0	(25.4.74) and 6.15 a.m
WITH	26.4.74	6.15a.m.	29.2	39.0	(26.4.74) is equal
GLASS					to 33.1°C.
COVER	30.4.74	3.30p.m.	41.0	85.1	Drop in temperature
ONLY		7.35p.m.	36.0	68.7	between 7.35 p.m.
		10.40p.m.	32.0	56.1	(30.4.74) and 6.30a.m.
	1.5.74	6.30a.m.	28.0	38.5	(1.5.74) is equal to
					30.2°C.
	2.5.74	3.45p.m.	42.0	83.5	Drop in temperature
		7.45p.m.	36.0	74.0	between 7.45p.m.
		11.15p.m.	32.5	67.0	(2.5.74) and 6.15a.m.
WITH	3.5.74	6.15a.m.	28.3	56.1	(3.5.74) is equal
ADDI-					to 17.9°C
TIONAL	5.5.74	4.15p.m.	41.8	87.5	Drop in temperature
INSULA-		8.00p.m.	33.7	77.6	between 8.00p.m.
TION		11.30p.m.	31.5	69.3	(5.5.74) and 7.00a.m.
COVER	6.5.74	7.00a.m.	28.2	56.8	(6.5. 74) is equal
					to 20.8°C.

3-4 CONCLUSIONS AND RECOMMENDATIONS

The solar water heater combines collection and storage. Therefore, it does not require a separate water storage tank used in conventional units operating on the thermosiphon principle. The additional cost of storage tank has thus been eliminated.

The direct contact type of solar water heater combining collection and storage is more efficient and cheaper than the conventional tube-plate type collector.

Tests have indicated that it is economical to operate the heater under steady flow conditions. Collection efficiency as high as 72% has been obtained with a mass flow rate of 75.9 kg/h.

Under conditions of utilization where the water temperature is not expected to exceed 60°C , the collection efficiency achieved is about 65%.

The energy losses from the collector in the evening hours are considerable. To reduce these losses more than one glass plates may be used for the top covers. For any given absorber-plate temperature, the limitation to this approach will arise because each extra glass plate cover reduces energy input to the absorber plate.

If the gap between the absorber plate and the lower plate is further reduced, the temperatures of water are expected to be considerably higher than those observed, at any time of the day (particularly in the morning hours). Such a unit may be advantageous for use in indirect heating of the generator of a vapour absorption system of refrigeration.

The insulation provided at the back is sufficient to maintain the energy losses from the back plate to the surroundings at a negligible low level as compared with the upward energy losses.

To reduce the upward energy losses at high temperatures, a better method may be to make the collector surface wave-length selective.

The calculated hourly rise in the water temperature by using Hottel's equation for the overall heat loss coefficient is within 0.147 to 0.946 % of the experimentally measured values. Thus Hottel's equation gives values which are close to the experimentally measured values for absorber plate temperatures in the range of 30 - 86°C.

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APPENDIX-A

```
      READ,N
      READ,PHI,BETA
C     PHI IS THE LATITUDE (26.5°) AND BETA IS THE
      INCLINATION OF THE COLLECTOR WITH THE HORIZONTAL
      RS = (1.+COS(BETA))/2.
C     RS IS THE ORIENTATION FACTOR FOR THE SKY RADIATION
      DO 10 I=1,N
      READ, HD, HS, T, DELTA
C     HD IS THE DIRECT RADIATION, HS IS THE SKY RADIATION
C     T IS THE SOLAR TIME AND DELTA IS THE DECLINATION
      OMEGA=(ABS(T - 12.))/12.
C     OMEGA IS THE HOUR ANGLE
      PHIB=PHI-BETA
      COST=SIN(PHIB)*SIN(DELTA)+COS(PHIB)*COS(DELTA)
                                          *COS(OMEGA)
      COSHT=SIN(PHI)*SIN(DELTA)+COS(PHI)*COS(DELTA)
                                          *COS(OMEGA)
C     T AND HT ARE THE SUN'S INCIDENCE ANGLES WITH THE
C     HORIZONTAL AND THE TILTED SURFACE RESPECTIVELY
      RD=COST/COSHT
C     RD IS THE ORIENTATION FACTOR FOR DIRECT RADIATION
      PRINT,T,HD,HS,HT
C     HT IS THE TOTAL RADIATION INCIDENT NORMALLY
C     ON THE TILTED COLLECTOR SURFACE
      CONTINUE
      STOP
      END
```

APPENDIX-B

```
      DIMENSION TW(20),H(20),TO(20),TP(20)
C     TW IS THE ARITHMETIC MEAN OF WATER TEMPERATURES
C     AT THE START AND END OF AN HOURLY INTERVAL-H IS
C     THE AVERAGE HOURLY INCIDENT RADIATION-TO IS THE
C     AVERAGE AMBIENT TEMPERATURE-TP IS THE AVERAGE
C     ABSORBER PLATE TEMPERATURE-M IS THE MASS OF WATER
C     CONTAINED PER SQUARE METER OF THE COLLECTOR SURFACE
      REAL M
      DO 20 KING=1,4
      READ, M, HO,CO,N
      N1=N-1
      READ,(TW(I),I=1,N)
      READ,(H(I), I=1,N1)
      READ,(TO(I),I=1,N1)
      READ,(TP(I),I=1,N1)
      PRINT 6
      EG=0.96
      EP=0.95
      TAU=0.90
      ALPHA=0.95
      SIGMA=4.9E-08
      C=1.0
      EN=(1.0/EP)+(1.0/EG)-1.
      AN=SIGMA/EN
      DO 10 I=1,N1
      IP1=I+1
      QU=M*C*(TW(IP1)-TW(I))
C     QU IS THE USEFUL ENERGY
      QA=TAU*ALPHA*H(I)
C     QA IS THE ABSORBED ENERGY
      QL=QA-QU-QB
C     QB IS THE ENERGY LOSS FROM THE BACK OF THE
C     COLLECTOR AND QL IS THE UPWARD ENERGY LOSS
      TG=TP(I)
C     TG IS THE ITERATIVE GLASS PLATE TEMPERATURE
      DO 13 K=1,6000
```

```
      TG=TG-0.1
      QPGR=AN*(TP(I)**4-TG**4)
      TF=TP(I)-TG
      SRTF1=SQRT(TF)
      SRTF2=SQRT(SRTF1)
      QPGC=CO*TF*SRTF2
C     QPGR IS THE RADIATION LOSS FROM THE PLATE TO GLASS
C     QPGC IS THE CONVECTION LOSS FROM THE PLATE TO GLASS
C     CO IS THE CONVECTION COEFFICIENT
      QSUM2=QPGR+QPGC
      IF(QSUM2.GE.QL)GOTO14
13    CONTINUE
14    TGF=TG
C     TGF IS THE REQUIRED TEMPERATURE OF THE GLASS
      TS=TGF
C     TS IS THE ITERATIVE SKY TEMPERATURE
      DO 12J=1,6000
      TS=TS-0.1
      QGOR=SIGMA*EG*(TGF**4-TS**4)
      QGOC=HO*(TGF-TS)
      QSUM1=QGOR+QGOC
C     QGOR IS THE RADIATION LOSS FROM THE GLASS SURFACE
C     TO THE SURROUNDINGS AND QGOC IS THE CONVECTION LOSS
      FROM THE GLASS SURFACE TO THE SURROUNDING AIR
      IF(QSUM1.GE.QL)GOTO11
12    CONTINUE.
11    TSF=TS
C     TSF IS THE EQUIVALENT SKY TEMPERATURE
      PRINT 5,QPGR,QPGC,QGOR,QGOC,TGF,TSF,QL
10    CONTINUE
20    CONTINUE
6     FORMAT(8X,*QPGR*,8X,*QPGC*,8X,*QGOR*,8X,*QGOC*,
     1 8X,*TGF*,8X,*TSF*,8X,*QL*/)
5     FORMAT(2X,7F12.4)
      STOP
      END
```

APPENDIX-C

The fabrication of solar water heater does not involve any complicated and costly machining processes. All the materials used for fabrication are easily and cheaply available. A list of materials with cost is as given below:

Item	cost
G.I. Sheets 3 mm thick, $3m^2$	Rs. 150/-
Nuts, bolts and plane washers (7.5 x 36 mm),6kg.	Rs. 48/-
Glass plate 3 mm thick, 1.6 m^2	Rs. 48/-
Glass wool insulation 2 cm thick, $3m^2$	Rs. 45/-
Plywood sheet (12 mm), 1.7 m^2	Rs. 52/-
Nails and wood screws	Rs. 4/-
Chir wood 25 x 12.5 cm, 3 m long (half plank)	Rs. 40/-
Rubber gasket 3 mm thick, 5 cm wide and 12 m long	Rs. 48/-
Total	Rs. 435/-

Two technicians (one turner and one carpenter) can manufacture the heater in two days. Thus the total fabrication cost of the heater will not exceed Rs. 500/-.